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AN EARTHQUAKE CATALOGUE FOR TURKEY FOR THE INTERVAL 1913-1970

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SUMMARY - An earthquake catalogue is presented for the whole area of Turkey within latitude and longitude limits equal to 35.5° N to 42.5° N and 25.5° E to 45.0° E, respectively, for the interval 1913-1970. Source parameters (origin time, epicentral coordinates, focal depth) have been calculated on computer, as far as available data permit. For magnitude determinations, a consistent scheme has been adhered to for the whole period under investigation. Our aim has been to achieve the .highest possible homogeneity in tabulated material over the whole interval, coupled with maximum possible completeness and reliability. All results, including error computations, are compiled in a catalogue. The catalogued data may serve as a basis for continued investigations of Turkish seismicity, as well as a source of information for all other purposes concerned, such as for engineering.

INTRODUCTION

Turkey is one of the seismically most active countries in the world, and the long Turkish history can report many catastrophes due to earthquakes. This constitutes no doubt valuable information in itself, but for modern seismology, with its requirements for accuracy, usually only instrumentally recorded events can be used. Therefore, the period available for investigation restricts itself to the present century. But the number and quality of seismological stations have been in steady increase over all the past decades of this century, and this development is still' going on. With such a dynamic evolution, it is hardly possible to prepare a catalogue which would be equally complete and equally accurate over the whole period 1913-1970. Instead, we have to face an increasing completeness of data with time, a fact that has to be carefully borne in mind in any use of the results presented here.

Already a number of valuable earthquake catalogues have been published for the Turkish area, such as by Pinar and Lahn (1952), Ergin et al. (1967), Öcal (l968ab), Ergin et al. (1971), Shebalin et al. (1974), Crampin and Ucer (1975), and particularly by Kárník (1968, 1971), all of them with further references. In these catalogues generally only compilations of source data from various other publications were made without recalculations, and therefore they naturally do not always reach the degree of homogeneity which could be achieved by a consistent treatment of all data. In the present undertaking, we therefore consider it important to achieve the highest possible homogeneity, coupled with highest possible accuracy and completeness. To this end, calculations on an electronic computer are made for all source parameters, when data are enough to justify this treatment. Moreover, magnitudes have been calculated according to a consistent scheme for the whole period under investigation.

The purpose of the catalogue is thus to meet the demands of modern seismology, as far as possible. It could serve as a basis for further investigations of Turkish seismicity, and as a source of information for various applications, especially in engineering.

DATA SOURCES

The basic data needed for our investigation consist of P-wave readings a seismograph stations. The following data sources have been used:

1) For the interval 1913-1917, the monthly bulletins of the British Association for the Advancement of Science.

2) For the interval 1918-1963, the bulletins of the International Seismological Summary (ISS).

3) For the interval 1953-1963, also the bulletins of the Bureau Central International de Seismologie (BCIS), Strasbourg, for the reason that ISS reports only events of larger magnitudes for this period.

4) For the interval 1964-1970, the bulletins of the International Seismological Centre (ISC) at Edinburgh.

5) For the years prior to 1913, available catalogues, especially from the Bureau at Strasbourg, as well as individual station bulletins, were searched, but found too scanty and unreliable to justify inclusion in our catalogue.

6) As the completeness of the material would be limited by the completeness or the lack of it in the sources used under 1) to 4), we also compared with other available catalogues of Turkish earthquakes.

Concerning the space limitation of our data, we have to consider that earthquake zones frequently cross national boundaries. For example, there is a practically continuous seismic belt from the North Anatolian fault zone to adjacent parts of Caucasus and Iran and similarly there is no boundary between seismicity in western Anatolia and in the Aegean Sea. In our catalogue we have essentially limited ourselves to Turkish territory, but, especially for the regions mentioned, also some events from beyond the borders are included, thus providing better continuity with corresponding catalogues from these adjacent areas. We have essentially limited our area to latitudes 35.5° N to 42.5° N and longitudes 25.5° E to 45.0° E., i.e. an area of about $1.3 \cdot 10^6$ km^2. It should also be emphasized that the whole Turkish area is involved, while the UNESCO – inspired Balkan Project includes only the western part of Anatolia.

COMPUTER PROGRAM AND ITS APPLICATION

For the calculation of source parameters several available computer programs were considered. We have been using a program developed in 1972 at the Bureau Central International de Séismologie (BCIS) at Strasbourg under the direction of Professor J.P. Rothé.

This program is based on a method of iterations which computes the true hypocenter and origin time of an earthquake by use of an approximate hypocenter and origin time determined with a preliminary calculation. In our case, we used as preliminaries the coordinates of epicenter and origin time which were calculated by the data source used (ISS, BCIS).

The basic equation in the program is the equation which gives the station travel-time residual:

$$u_i = (T_i - H) - t_i \qquad (1)$$

where

T_i = arrival time of a phase at the i^{th} station

H = approximate origin time

t_i = calculated travel time for the i^{th} station.

Since the arrival time T_i can be given as a function of origin time, epicentral distance and depth, $T_i = f(H, \Delta_i, h)$, equation (1) gives the changes in arrival time and takes the following form:

$$u_i = dH + (X \sin \alpha_i + Y \cos \alpha_i) (\partial t/\partial \Delta)_i + z (\partial t/\partial h)_i \qquad (2)$$

where

dH = change in origin time

X = $\cos \varphi \, d\lambda$

φ = latitude of epicenter

$d\lambda$ = change in longitude

Y = $d\varphi$ = change in latitude

Z = dh = change in depth

α_i = azimuth epicenter to station i.

Here, dH, X, Y, and Z are the unknowns. To obtain these unknown parameters, n equations of type (2) (n is equal to the number of stations used) are solved by the method of least squares, with the condition that Σu_i^2 = minimum.

More detailed descriptions connected with this program can be found in Rothé et al. (1972abc).

While testing the computer program, a number of modifications were made in its application as well as other results found, which can be summarized as follows.

1) In an original version of the program a combination was made of a so-called Balkan crust and the Herrin earth model (Herrin et al., 1968). This proved unreliable, as it involved structural inconsistencies, and for this reason the Herrin model is used exclusively, also for the crust. We did not find any seismic profiling results for Turkey, but the model anyway appears justified for this area.

2) A consequence of using entirely the Herrin model is that only P-wave readings can be used and no S-wave readings, as the tables of Herrin et al. (1968) do not contain the corresponding set of S travel times.

3) In an original effort, we let the corrections of coordinates and origin time as well as of the focal depth be unknown. This led to instability in many cases, naturally mostly in cases with scanty data. Therefore, it was necessary to keep one of these parameters fixed and calculate the others. This is done such that we let focal depth h assume a series of assigned values: 0, 10, 20, 30, 40, 50, 60, 70 and 80 km, and for each of these depths, the other parameters are calculated. Then, the errors Σu_i^2, one value for each calculation, are plotted versus focal depth. The focal depth which gives the smallest error is taken as the true focal depth (to the nearest 10 km), and the corresponding epicentral coordinates and origin time are tabulated. When no error minimum is obtained for the depth range 0-80 km, calculations are continued for greater depths (100, 120, 140, … to 200 km, in steps of 20 km) until an error minimum is found. In some isolated cases, especially when data are scanty, such as of smaller events or of older date, obviously erroneous depths are obtained. In such cases, the focal depth is assumed to agree with reliably determined depths for other events in the same location.

4) To judge the reliability of the results, our catalogue contains the number of stations used in each calculation together with standard deviations of epicentral coordinates and of origin times. For the focal depths, the errors can generally be given as ± 5 km for h ≤ 80 km and ± 10 km for h > 80 km, referring to 3) above, and are not repeated in our catalogue.

5) For the interval 1964-1970, when ISC information is used (see above), several test computations showed agreement with ISC, in general well within error limits. See Table 1. Therefore, no recomputations are made for this interval. This also affords a comparison between using Jeffreys-Bullen model (ISC) and the Herrin model (our determinations).

6) On the other hand, as a result of our recomputations, we found that some of the earlier events which should be included according to the original data source used, in fact are located outside our area. They are therefore excluded from the main catalogue, but for the reader's convenience we have collected such cases in Table 2.

MAGNITUDES

Magnitudes are nowadays considered as earthquake parameters of the same significance as epicentral coordinates and origin time, quite correctly. In working up material for many years, especially from older date, special requirements must be placed upon the magnitude determinations, to make them reliable and useful for further investigations. Such requirements could be summarized as

1) A need to have consistent (homogeneous) magnitudes throughout the whole series investigated, avoiding jumps from one scale to another.

2) A need to know clearly how the magnitudes have been calculated and their relation to other well established scales as well as to seismic wave energy E and other source parameters.

These requirements have been of mandatory significance in our determination of magnitudes for Turkish earthquakes. The requirement 1) can be best fulfilled if the same instruments have been operating all the time. This is the case only with few instruments. In our determinations much use has been made of the Uppsala Wiechert records. This seismograph, installed in 1904, is still operating and has had practically unchanged characteristics throughout all this time, as evidenced by fairly frequent determination of the instrumental characteristics. It is not of extremely great importance to use any particular scale, whereas, on the other hand, the need 2) is very important. Whatever scale is used, it should be possible to recalculate the magnitudes into those of any other standard scale.]

As in recent years, especially after 1970, Turkey has been equipped with a dense network of stations, especially in its western part, there will for later years also be reason to develop local magnitude scales. Also in that work it is very important to get scales which bear well defined relations to other established scales (see Båth, 1966). One difficulty in such works, as evidenced from other earthquake areas, is to find earthquakes with good records both at local and distant stations, for comparison. However, such difficulties could be overcome by a clever combination of records and instruments, possibly including strong-motion instruments for the local recordings.

Zurich recommendations. In our magnitude calculations, we have adhered to the internationally adopted Zurich recommendations of 1967 (see Båth, 1969). In summary, they imply the following two formulas (A = ground amplitude, microns, T = period, sec).

For body-wave magnitude m (essentially from PZ'):

$$m = \log A/T + q\ (\Delta, h) \qquad (3)$$

where the calibrating term q (Δ, h) is obtained from Gutenberg and Richter (1956), and
for surface-wave magnitude M (from horizontal Rayleigh waves):

$$M = \log A/T + 1.66 \log \Delta^{\circ} \pm 3.3 \qquad (4)$$

for 10 sec ≤ T ≤ 30 sec.

A magnitude formula of type (4) was discussed already by Båth (1956). For dominating surface-wave periods of Swedish records of Turkish earthquakes, i.e. around 10-15 sec, M-values according to (4) would exceed those of the Gutenberg (1945) formula by about 0.3 (even though the latter is strictly not applicable to such low periods). However, in this case, this difference is almost exactly eliminated by the difference in attenuation between shorter periods as here versus 20 sec period. Hence, our magnitudes correspond to what 20 sec period waves would give, using Gutenberg's formula, under the condition of equal energy release. Therefore, formulas, like E-M relations etc, are still valid.

Uppsala Wiechert surface-wave magnitudes. Searching Uppsala seismological bulletins and Wiechert records for Turkish earthquakes, it soon became evident that only the surface-wave magnitude M would be able to provide something like complete information, there being far too few cases where Wiechert had recorded body phases to justify calculation of m. A disadvantage could arise from the use of only one station – Uppsala. However, the deviation this would cause from any "true" magnitude is unlikely to be greater than the error inevitably inherent inmost magnitude determinations.

This procedure would guarantee magnitudes of as high a homogeneity as possible for the whole period of investigation. However, we deemed it superfluous to continue the magnitude determination from Wiechert records far beyond the time when modern instruments of higher sensitivity have come into use, i.e. after the 1950's. Therefore, M from Uppsala Wiechert was determined up to 1959, incl. This provides enough of overlapping years during the 1950’s to make it possible to reduce the Wiechert M-values to any other scale, by making double or triple determinations for each event, from different, instruments or different stations.

Relations between different scales. We have chosen to refer all values to the surface-wave magnitude scale. M, corrected for depth whenever necessary, for the following reasons:

1) Uppsala Wiechert records are available for the whole period of investigation;

2) M-values generally exhibit greater stability than m-values, at least when only one or a few stations are available;

3) The majority of earthquakes in our area occur at shallow depth.

As a measure of the magnitude M, we have chosen the average $\overline{M}$ of M(UPP), derived from long-period Benioff instruments, and M(KIR), derived from Galitzin instruments. This is identical to the M-values regularly reported in the monthly seismological bulletins from Uppsala, and corresponds well to the internationally adopted M-scale. Source and station corrections have been ignored in (4), as results by Båth (1956) convince us that such corrections would be insignificant in the present case.

For a consistent calculation of M, defined in this manner, over the whole period of investigation, a number of regression equations had to be derived from parallel recordings, making it possible to reduce any given magnitude to the adopted M-scale. For this purpose, the following equations were computed by least-squares techniques, where N = the number of pairs of observations (= number of earthquakes) in each case and internationally adopted abbreviations for stations are used:

$$\left.\begin{aligned} M(UPP) &= 1.01\,M(KIR) - 0.17 \qquad N = 221 \\ M(KIR) &= 0.91\,M(UPP) + 0.58 \qquad N = 221 \end{aligned}\right\} \tag{5}$$

where M(UPP) and M(KIR) are defined as just mentioned. Equations (5) permit us immediately to express the average $\overline{M}$ in M(UPP) or in M(KIR) alone:

$$\overline{M} = \tfrac{1}{2}\,[\,M(UPP) + M(KIR)\,] = 0.95\,M(UPP) + 0.29 = 1.01\,M(KIR) - 0.08 \tag{6}$$

Likewise we find

$$\overline{M} = 0.85\,M(W) + 1.04 \qquad N = 51 \tag{7}$$

where M(W) is the Wiechert magnitude (similar results concerning a comparison of Wiechert and Benioff at Uppsala are reported by Båth, 1959, p. 21).

When surface-wave records are unavailable, we have used m determined from short-period vertical-component P-wave records, in the first hand at UPP and KIR, for the test possible correlation with $\overline{M}$. $\overline{m}$ is defined as their average:

$$\overline{m} = \tfrac{1}{2}\,[\,m(UPP) + m(KIR)\,] \tag{8}$$

and the regression of $\overline{M}$ on $\overline{m}$ becomes, derived for h ≤ 45 km:

$$\overline{M} = 1.46\,\overline{m} - 2.91 \qquad N = 63 \tag{9}$$

When only m(UPP) or m(KIR) is available, we use the following regressions:

$$\left.\begin{aligned} \overline{M} &= 1.30\,m(UPP) - 1.91 \qquad N = 90 \\ \overline{M} &= 1.45\,m(KIR) - 3.04 \qquad N = 66 \end{aligned}\right\} \tag{10}$$

Moreover, we deduced the following regression equations:

$$\left.\begin{aligned} \overline{M} &= 1.54\,m(SKA) - 3.19 \qquad N=17 \\ \overline{M} &= 1.15\,m(UME) - 1.47 \qquad N=19 \\ \overline{M} &= 1.13\,m(UDD) - 1.30 \qquad N=17 \\ \overline{M} &= 1.25\,m(DEL) - 1.78 \qquad N=17 \\ \overline{M} &= 0.86\,m(KLS) + 0.59 \qquad N=7 \end{aligned}\right\} \tag{11}$$

In equations (5) to (7), which contain only surface-wave magnitudes M, we combine all available events, irrespective of focal depth, while in (9) to (11), containing both M and m, we have to restrict ourselves to shallow depth (h ≤ 45 km) in their derivation.

When no record is available from the Swedish network, we searched available bulletins and included magnitudes determined by other agencies, but only in cases when relatively long series are available which permit regression equations to our magnitudes to be calculated. We thus derived the following equations:

$$
\left.
\begin{array}{ll}
\overline{M} = 1.47\ m(US) - 2.16 & N = 115 \\
\text{where US stands for USCGS, presently NEIS, and} & \\
\overline{M} = 1.55\ m(ISC) - 2.49 & N = 110 \\
\overline{M} = 1.15\ M(ATH)_1 - 1.06 & N = 18 \\
\overline{M} = 0.65\ M(ATH)_2 + 1.77 & N = 15 \\
\overline{M} = 0.96\ M(ATH)_3 + 0.35 & N = 68
\end{array}
\right\} \quad (12)
$$

The ATH magnitudes had to be divided into three groups, as indicated, because different formulas have been used in different periods of time: $M(ATH)_1$ refers to 1952-1958; $M(ATH)_2$ refers to 1959 up to June, 1965, incl., during which period in fact two slightly different formulas were used, but the results of the earlier one (used 1959-1961) have here been reduced to the later one; $M(ATH)_3$ finally refers to July, 1965 to 1970 and is most nearly equivalent to the M_L-scale.

In all the regressions given, we have attempted direct relations between the sought quantity M and the respective given quantity, as this will guarantee the highest possible accuracy in the conversions. Use of successive relations as intermediate steps, will rapidly accumulate errors, and has therefore been avoided completely. Likewise, inversions of the given formulas are strictly not permitted, as these will also lead to inaccuracies due to observational scatter, and have therefore also not been made in any of our applications. For the reader's convenience we have computed several conversion formulas, by which our magnitudes can be recalculated into some other scales:

$$
\left.
\begin{array}{ll}
\overline{m} = 0.52\ \overline{M} + 2.92 & N = 63 \\
m(US) = 0.70\ \overline{m} + 1.19 & N = 141 \\
m(ISC) = 0.69\ \overline{m} + 1.18 & N = 138
\end{array}
\right\} \quad (13)
$$

valid for all focal depths. Finally, it should be remarked that all our conversion formulas apply strictly only to the Turkish area investigated and to records from specified stations or agencies, and generalizations of these results could only be made after special examination.

In calculation of m, focal depth is already taken into account in (3). But for M, calculated from (4), it will be necessary to apply a depth correction. The depth correction to M should be such that the corrected M-value will yield the correct energy E of the earthquake, irrespective of its depth. Depth corrections (see for example Båth, 1952, 1956) may vary strongly" from case to case, and for this reason we have attempted to determine a depth correction applicable especially to our case. We have determined the depth correction ΔM in the following way:

$$\Delta M = (M)_{calc} - (M)_{obs} \quad (14)$$

where $(M)_{calc}$ is obtained from (9), where h is taken into account, while $(M)_{obs}$ is from (6), i.e. without depth correction. Correlating ΔM with h results by least-squares techniques in the following fairly well defined relation:

$$\Delta M = 0.0046\ (h - 50) \qquad \text{for } h \geq 50 \text{ km}, \quad N = 55 \quad (15)$$

This leads to the following depth corrections to be applied to M-values obtained from surface-wave records:

h =	70	80	100	120	140	160	180	200 km
AM =	± 0.1	± 0.1	± 0.2	± 0.3	± 0.4	± 0.5	± 0.6	± 0.7.

Magnitude calculation procedure. With the regression equations given, the calculation of magnitudes proceeds in each case as follows:

1) If both M(UPP) and M(KIR) are available, we calculate M directly from $M = \frac{1}{2}[M(UPP) + M(KIR)] + \Delta M$.

2) If only M(UPP) or only M(KIR) is available, we calculate $\overline{M}$, using (6) and apply depth correction ΔM.

3) If neither M(UPP) nor M(KIR) is available, we calculate $\overline{M}$ from M(W), using (7), and apply depth correction ΔM.

4) If no long-period (surface-wave) information is available, we calculate M from short-period records of P, in the first hand from $\overline{m}$, obtained as the average of m(UPP) and m(KIR), using (9). Note that in using short-period P-wave (m), M is identical to $\overline{M}$ and no depth correction should be applied.

5) If only m(UPP) or m(KIR) is available, but not both, we get M from (10).

6) If neither m(UPP) nor m(KIR) is available, we use m from some of our other stations or from other agencies, apply the respective regression equations (11) and (12) to get M, and tabulate an average of these M-values, when more than one determination is available.

7) When no readings are available, it is still generally possible to give an upper limit of the magnitude. For the period 1913-1951, this is estimated as 4.6, using Uppsala Wiechert instrument, and from 1952 onwards the upper limit is assigned as 4.0 in such cases. However, when data permit a determination, this is given also in cases when M falls below this limit.

8) The number of observations (recording stations = n) may provide a rough estimate of magnitude, which could be of some use especially for $M \leq 5$. From the catalogue data for 1970 we derive the following equation:

$$M = 0.81 \log n + 3.03 \qquad N = 258 \qquad (16)$$

with a standard deviation of calculated M of only ± 0.36. As n serves as a measure of recording distance, it is natural that M depends on log n, and with an even distribution in all directions of equally sensitive stations, such a relation would be even more perfect. Due to increasing station density and quality with time, the numerical values of the coefficients certainly depend on the year used. Even though (16) can be used for approximate estimates for $M \leq 5.0$, no use has been made of it in our catalogue. An alternative to (16) is to relate M to maximum recording distance.

Concerning the accuracy of the resulting magnitudes, we can state the following:

1) M as determined from an average of M(UPP) and M(KIR) can be considered as the "correct" value, at least in our choice of reference scale, even though this value, like all the others, are subject to some uncertainty due to focal mechanism and azimuthally unequal radiation from the source.

2) M(UPP) and M(KIR) are strongly correlated to each other and to their average, the correlation coefficient between M(UPP) and M(KIR) being + 0.958 ± 0.005 from N = 221 pairs of observations. This guarantees high reliability of M, even when calculated from M(UPP) or M(KIR) alone.

3) The standard deviation of M as calculated from M(W), amounts to ± 0.14 (N = 49).

4) When we have to depend exclusively on short-period P to calculate M, the scatter somewhat increases. For example, calculating M from m results in a standard deviation of ± 0.34 (N = 63), and averages of other determinations SKA-KLS, US, ISC, ATH, yield M with a standard deviation of ± 0.28 (N = 77). Also, the correlation between short-period m-determinations from UPP and KIR is ±0.903 ± 0.011 (N = 294), which is still quite high but nevertheless significantly smaller than the correlation between M(UPP) and M(KIR) from long-period records, given under item 2) above.

5) As regression equations have been derived mostly for events with M over 4, they become increasingly inaccurate when applied to events with M less than 4. As we shall see in the following section, this is of no great consequence, as indication of small magnitudes ($M < 4.0$) serves the purpose of classification,

but in addition to this, such small events are of no great concern neither energetically nor tectonically, or otherwise.

All in all, our tabulated magnitudes are believed to be as homogeneous and reliable as possible, and more dependable in applications than an uncritical mixing of magnitudes from different scales.

COMPLETENESS OF CATALOGUE

We aimed at the outset at homogeneity and completeness of the catalogue. Such aspects have to be laid both upon data availability and on data handling. Data availability is far from homogeneous, and a glance at the catalogue will immediately convince us about the abundance of data in the latest years compared to the earliest ones. On the other hand, data handling which fell on our lot, has at least aimed at homogeneity, in calculation of all source parameters, including magnitude. However, the inhomogeneity created by data availability can be off set or eliminated if we are able to assign some magnitude limit, above which the catalogue can be considered as homogeneous and also reasonably complete, but below which these conditions are not fulfilled.

1. A common method to test completeness of data is to check the relation

$$\log N = a - b\,M \qquad a, b \text{ constants} \tag{17}$$

This was done for an early, an intermediate and a late period of time from our catalogue, with results presented in Fig. 1 and Table 3. It is customary to assume completeness of data as far down on the M-scale as the line (17) remains reasonably satisfied, with a reliable slope determined from the larger events where data are known to be complete. However, the number of larger' events is generally too small to permit a reliable slope determination. Anyway, from this judgment we would conclude completeness of our data for 1918-1930 and for 1946-1955 down to around M = 5, while 1964-1970 would be complete down to M nearly = 4. However, we have to observe that comparing the three intervals chosen for investigation (Table 3), there is not only a gradual increase of the slope b but also, and above all, an increase in level a. Note also that even with no change of slope, i.e. two lines $\log N = a - b\,M$ and $\log N' = a' - b\,M$ with only a difference $a - a'$ in level, we have $\log(N/N')$ = constant or N/N' = constant, which implies that the difference $N - N'$ still increases with decreasing M.

We can point to two factors which could have such consequences: partly the well-known increase in station density and station quality within the last decade, partly the variation with time of Turkish seismicity, the great earthquake of 1939 being the starting point of a relatively active period. Both effects could lead to increased slope and increased level in the later periods compared to earlier years. And the lower magnitude limit cannot be stated with such a certainty as indicated above. The upper part of Fig. 2, showing the annual sums of earthquakes within our area with M ≥ 5.5, would rather favour the idea of fluctuations in seismic activity, the later period not being particularly pronounced.

2. Another test on the completeness of data is made by plotting released energy E versus time. E in ergs is calculated from

$$\log E = 12.24 + 1.44\,M \tag{18}$$

and summed annually and added (Fig. 2). The straight line exhibits the average strain energy accumulation during our period of observation, amounting to $3.3 \cdot 10^{22}$ ergs/year, equivalent to one earthquake of magnitude M = 7.1 per year within our area. This is quite a remarkable energy accumulation and release, about 16 times as large as that of the East African rift system, reduced to the same area (Båth, 1975). However, we have to remember that for demonstrating homogeneity of material, the energy method is not particularly sensitive, as he energy depends almost totally on the largest events only.

3. The well-known magnitude difference between a main earthquake and its largest aftershock, amounting to about 1.2 (the so-called Båth's law, cf. Richter, 1958, p. 69) could provide some test on the completeness of our catalogue. Table 4 lists all events with M ≥ 7.0 and their largest aftershocks, if any have

been found, as well as the magnitude difference. It is probably symptomatic that no aftershocks are found for the first two events (nor for some later ones). The average difference is about 1.7 which may be regionally influenced.

4. The limitation of our catalogue is dominated by the limitation in the data sources used, which in turn depends on availability of stations and their reports. While it is possible with fairly good reliability to assign a magnitude limit, above which homogeneity prevails, for a limited period of a few years, as done above, especially for 1964-1970, it becomes increasingly difficult to assign a corresponding limit valid throughout the whole catalogue from 1913 to 1970. However, on the basis of (the various attempts described here, we would estimate such a limit as lying around 5.5 on the M-scale. The abundance of data in later years concerns almost exclusively low magnitudes.

On the basis of these considerations, we have introduced Reference Numbers (left column in our catalogue), for events with M ≥ 5.0 only, by which these more important events can be grasped at a glance out of the multitude of smaller events. Events with M ≥ 6.0 are marked on a map (Fig. 3), which also shows the division into regions (R), which are used for our geographical index given at the end. The geographical index will make it possible to find easily for any given region all earthquakes listed in our catalogue for which M ≥ 5.0. The regional distribution of energy and number is given in Table 5 and in Fig. 4, where it should be observed that by virtue of eq. (18) the largest events dominate. It should also be emphasized that the presentations in Fig. 3 and 4 and Table 5 only serve the purpose of giving the dominating trends of the Turkish seismicity, while the recomputations listed in our catalogue in general permit geographically and tectonically much more detailed studies to be made.

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Table 1

Comparison between ISC and our determinations

Date	ISC determination	Our determination
Sep 2, 1968	$35.4^0 \pm 0.12^0$ N; $27.60^0 \pm 0.14^0$ E 23h 03m 44s ± 1.5 85 ± 16 km	$35.35^0 \pm 0.12^0$ N; $27.56^0 \pm 0.15^0$ E 23h 03m 46.31s ±1.19 80 km
Sep 28, 1968	$40.49^0 \pm 0.052^0$ N; $26.38^0 \pm 0.070^0$ E 00h 53m 28.0s ± 0.48 28 km	$40.42^0 \pm 0.05^0$ N; $26.51^0 \pm 0.07^0$ E 00h 53m 27.24s ± 0.47 10 km
Sep 28, 1968	$41.75^0 \pm 0.042^0$ N; $32.1^0 \pm 0.22^0$ E 03h 25m 53s ± 2.2 38 ± 18 km	$41.72^0 \pm 0.04^0$ N; $31.98^0 \pm 0.08^0$ E 03h 25m 55.71s ± 0.52 50 km
Mar 25, 1969	$38.78^0 \pm 0.035^0$ N; $28.51^0 \pm 0.059^0$ E 13h 28m 50.1s ± 0.47 40 ± 4.9 km	$38.80^0 \pm 0.08^0$ N; $28.47^0 \pm 0.14^0$ E 13h 28m 52.12s ± 0.68 40 km
Apr 2, 1969	$39.57^0 \pm 0.030^0$ N; $25.46^0 \pm 0.035^0$ E 13h 03m 26.4s ± 0.26 0 km	$39.54^0 \pm 0.05^0$ N; $25.44^0 \pm 0.06^0$ E 13h 03m 28.53s ± 0.44 10 km
Apr 6, 1969	$38.33^0 \pm 0.095^0$ N; $26.5^0 \pm 0.15^0$ E 12h 50m 29s ± 1.1 57 ± 17 km	$38.32^0 \pm 0.10^0$ N; $26.72^0 \pm 0.15^0$ E 12h 50m 29.27s ± 0.95 40 km
Apr 12, 1969	$40.29^0 \pm 0.058^0$ N; $42.92^0 \pm 0.058^0$ E 2h 07m 3.73s ± 0.65 62 ± 7.8 km	$40.33^0 \pm 0.08^{0\ N;}$ $42.91^0 \pm 0.08^0$ E 23h 07m 34.93s ± 0.59 60 km
Apr 26, 1969	$36.71^0 \pm 0.047^0$ N; $28.50^0 \pm 0.075^0$ E 08h 25m 12s ± 1.4 13 ± 10 km	$36.71^0 \pm 0.05^0$ N; $28.60^0 \pm 0.09^0$ E 08h 25m 11.93s ± 1.11 10 km
Apr 27, 1969	$36.54^0 \pm 0.038^0$ N; $28.21^0 \pm 0.051^0$ E 10h 58m 26s ± 1.3 33 ± 10 km	$36.60^0 \pm 0.05^0$ N; $28.19^0 \pm 0.06^0$ E 10h 58m 28.87s ± 0.42 40 km
Apr 30, 1969	$39.12^0 \pm 0.021^0$ N; $28.52^0 \pm 0.029^0$ E 20h 20m 32s ± 1.2 8 ± 7.6 km	$39.11^0 \pm 0.03^0$ N; $28.57^0 \pm 0.04^0$ E 20h 20m 34.18s ± 0.23 10 km

Table 2

Revised earthquake locations, outside our area of investigation

ISS or BCIS				Revised					
Date	Origin time GMT	Latitude ⁰N	Longitude ⁰E	Origin time GMT	Latitude ⁰N	Longitude ⁰E	Depth km	Magn M	Number of obs
Feb 9, 1918	12 28 05	41.5	28.0	12 28 39.40 ± 4.05	39.39 ± 0.21	24.41 ± 0.53	60	5.5	9
Mar 17, 1918	13 45 05	36.0	28.0	13 45 02.32 ± 4.56	34.53 ± 0.34	28.52 ± 0.42	40	5.8	13
Nov 25, 1918	12 38 48	36.4	27.5	12 38 22.53 ± 13.97	33.90 ± 1.42	28.94 ± 1.27	40	5.1	6
Oct 25, 1919	17 53 20	37.0	26.0	17 54 35.50 ± 6.72	40.50 ± 0.45	20.84 ± 0.48	10	4.9	8
Feb 25, 1920	23 32 20	38.8	32.9	23 34 30.25 ± 1.54	40.39 ± 0.13	18.16 ± 0.13	50	5.4	6
June 4, 1923	20 33 00	35.5	25.5	20 33 40.25 ± 6.48	37.68 ± 0.-74	24.30 ± 0.45	120	5.4	9
May 12, 1924	14 30 50	42.5	26.0	14 31 19.16 ± 4.33	41.08 ± 0.75	21.67 ± 1.35	80	–	6
Sep 3, 1926	21 59 50	41.5	26.5	22 00 14.62 ± 3.19	41.96 ± 0.30	25.13 ± 0.29	100	–	15
Apr 18, 1928	19 22 37	41.7	26.3	19 22 53.56 ± 0.84	42.32 ± 0.08	25.23 ± 0.09	10	7.1	58
Dec 10, 1928	07 02 53	37.4	26.1	07 03 03.38 ± 1.16	36.50 ± 0.15	25.01 ± 0.16	40	4.9	27
Oct 23, 1932	17 42 47	35.5	27.6	17 42 32.69 ± 6.66	34.53 ± 0.85	26.64 ± 0.43	10	<4.6	5
Sep 24, 1933	13 21 15	35.5	27.6	13 21 12.21 ± 3.80	34.96 ± 0.41	27.59 ± 0.23	80	5.0	11
Oct 24, 1933	16 25 12	42.5	45.4	16 25 08.75 ± 2.02	42.94 ± 0.25	46.24 ± 0.28	10	<4.6	8
Aug 3, 1936	04 01 36	36.5	31.0	04 01 08.50 ± 2.33	34.01 ± 0.21	31.95 ± 0.14	10	<4.6	7
Feb 29, 1940	16 07 44	35.7	25.9	16 07 44.34 ± 0.36	35.05 ± 0.06	25.66 ± 0.04	10	6.0	34
Apr 12, 1947	14 05 09	40.2	25.6	14 05 17.23 ± 1.05	39.86 ± 0.13	25.23 ± 0.10	60	5.4	31
Apr 23, 1953	12 53 48	35.5	26.5	12 53 57.51 ± 0.14	35.33 ± 0.02	26.95 ± 0.03	120	5.3	5
May 16, 1953	02 52 11	35.5	27.0	02 52 13.50 ± 0.46	35.16 ± 0.06	27.15 ± 0.10	10	4.7	6
June 10, 1955	03 56 50	35.5	26.0	03 56 50.02 ± 1.91	35.01 ± 0.32	25.84 ± 0.31	10	4.4	5
July 8, 1956	13 05 22	36.9	26.0	13 05 35.72 ± 1.49	39.90 ± 0.16	23.54 ± 0.21	120	4.9	12
July 10, 1957	23 37 20	36.5	26.0	23 37 26.37 ± 0.73	36.33 ± 0.08	23.07 ± 0.09	50	4.4	14
July 15, 1957	19 09 42	36.0	26.0	19 09 47.43 ± 0.47	36.14 ± 0.08	23.02 ± 0.12	80	4.4	5
July 21, 1957	15 08 14	39.0	45.0	15 08 37.78 ± 4.46	39.86 ± 0.57	46.49 ± 0.54	40	<4.0	5
Aug 14, 1957	02 44 24	35.5	28.0	02 44 33.15 ± 0.61	35.28 ± 0.08	28.08 ±0.12	80	4.9	21
Jan 30, 1958	19 13 30	36.25	26.0	19 13 25.75 ± 0.62	34.91 ± 0.10	24.52 ± 0.14	60	4.8	14
Jan 17, 1959	07 53 59	35.5	28.5	07 53 59.80 ± 3.04	32.99 ± 0.39	28.07 ± 0.30	100	4.2	5
Jan 24, 1959	15 54 02	35.5	28.75	15 54 06.23 ± 0.13	35.29 ± 0.02	28.70 ± 0.02	50	4.5	4
Feb 15, 1959	05 48 12	37.0	31.0	05 47 55.00 ± 1.35	34.58 ± 0.15	31.95 ±0.12	80	5.3	11
Apr 22, 1959	21 45 42	40.0	26.0	21 45 54.75 ± 1.12	39.59 ± 0.13	25.02 ± 0.13	40	3.9	5
June 13, 1959	12 02 01	36.0	32.7	12 01 57.80 ± 0.58	34.78 ± 0.08	32.51 ± 0.07	60	5.7	37
Sep 8, 1959	08 54 47	35.5	28.0	08 54 53-31 ± 0.61	35.32 ± 0.08	27.99 -± 0.09	80	4.4	14
Sep 16, 1959	05 13 50	35.5	26.0	05 13 56.02 ± 0.62	34.86 ± 0.08	25.90 ± 0.04	50	6.6	48
Jan 30, 1960	09 57 02	35.5	32.0	09 57 09.09 ± 0.43.	35.37 ± 0.04	31.54 ± 0.11	10	4.6	8
Mar 17, 1960	23 42 00	35.5	26.5	23 42 00.43 ± 1.84	34.75 ± 0.27	25.75 ± 0.30	80	<4.0	12
Apr 28, 1960	16 33 25	35.5	27.0	16 33 26.67 ± 0.62	34.30 ± 0.08	26.55 ± 0.07	60	5.4	35
July 28, 1961	20 01 49	35.8	27.5	20 01 49.43 ± 0.64	35.04 ± 0.08	26.91 ± 0.10	70	4.6	8
July 28, 1961	20 20 30	35.7	27.0	20 20 30.68 ± 0.73	35.27 ± 0.15	26.91 ± 0.15	20	<4.0	5
Sep 10, 1962	09 36 28	35.6	27.5	09 36 27.01 ± 0.35	34.59 ± 0.04	26.64 ± 0.04	50	5.4	74
Mar 29, 1963	21 52 08	35.6	28.6	21 51 55.12 ± 5.06	34.02 ±0.71	26.43 ± 0.57	40	4.1	10

Table 3

Regression equations log N = a – bM for different intervals of time and the total area investigated (see Fig. 1), with N referred to half-unit intervals of M

Time interval	Magnitude interval	Regression equation
1918-1930 (13 years)	4.6-7.5	$\log N = (5.22 \pm 0.07) - (0.68 \pm 0.01)\,M$
		Reduced to 10 years:
		$\log N = (5.11 \pm 0.07) - (0.68 \pm 0.01)\,M$
1946-1955 (10 years)	4.6-6.0	$\log N = (5.41 \pm 0.05) - (0.73 \pm 0.01)\,M$
1964-1970 (7 years)	4.1-7.5	$\log N = (5.85 \pm 0.10) - (0.78 \pm 0.02)\,M$
		Reduced to 10 years:
		$\log N = (6.00 \pm 0.10) - (0.78 \pm 0.02)\,M$

Table 4

Comparison of magnitudes M of main earthquake with largest aftershock

Reference number*)	Magnitude M		Magnitude difference
	Main earthquake	Largest aftershock	
1402	7.1	–	–
1601	7.1	–	–
1907	7.0	(5.5)	(1.5)
2604	7.0	5.2	1.8
2608	7.3	5.1	2.2
2802	7.0	5.2	1.8
2805	7.0	5.9	1.1
3004	7.6	6.3	1.3
3907	7.1	–	–
3909	7.9	5.5	2.4
4212	7.0	–	–
4309	7.2	–	–
4404	7.2	5.5	1.7
4416	7.0	5.5	1.5
4801	7.2	5.6	1.6
4905	7.0	5.2	1.8
4907	7.0	5.3	1.7
5303	7.4	5.7	1.7
5502	7.0	5.3	1.7
5604 + 5605	7.4 + 7.3	6.2	1.2
5708	7.1	5.9	1.2
5711	7.1	5.9	1.2
6410	7.0	4.8	2.2
6704	7.2	5.0	2.2
7002	7.3	5.9	1-4

*) See explanation to Epicenter and Magnitude Index at the end.

Table 5

Regional distribution of energy release.
In each region (R, cf. Fig. 3), the upper figure gives $\sum E$ in 10^{20} ergs
and the lower gives $\sum N$, both referred to $M > 5.0$ and to 1913-1970

R	1	2	3	4	5	6	7	8	9	10
+0	224.5/8	0.3/1	0.4/1	450.7/3	456.5/13	0.3/1	1.1/1	–	2.9/5	39.0/10
+ 10	457.4/20	1216.5/36	1446.7/38	443.6/8	76.2/11	526.8/8	20.1/6	4400.4/17	272.9/15	25.9/7
+20	236.7/12	644.4/31	39.5/17	7.5/8	–	9.9/3	9.7/6	1.8/3	6.2/8	1557.5/12
+30	1434.9/42	1761.2/64	531.9/20	4.2/6	0.5/1	5.8/3	–	–	11.0/1	2.1/4

Latitude boundaries (right edge, top to bottom): 42.5°N, 41, 39, 37, 35.5°N

Longitude boundaries (bottom, left to right): 25.5° E, 27, 29, 31, 33, 35, 37, 39, 41, 43, 45° E

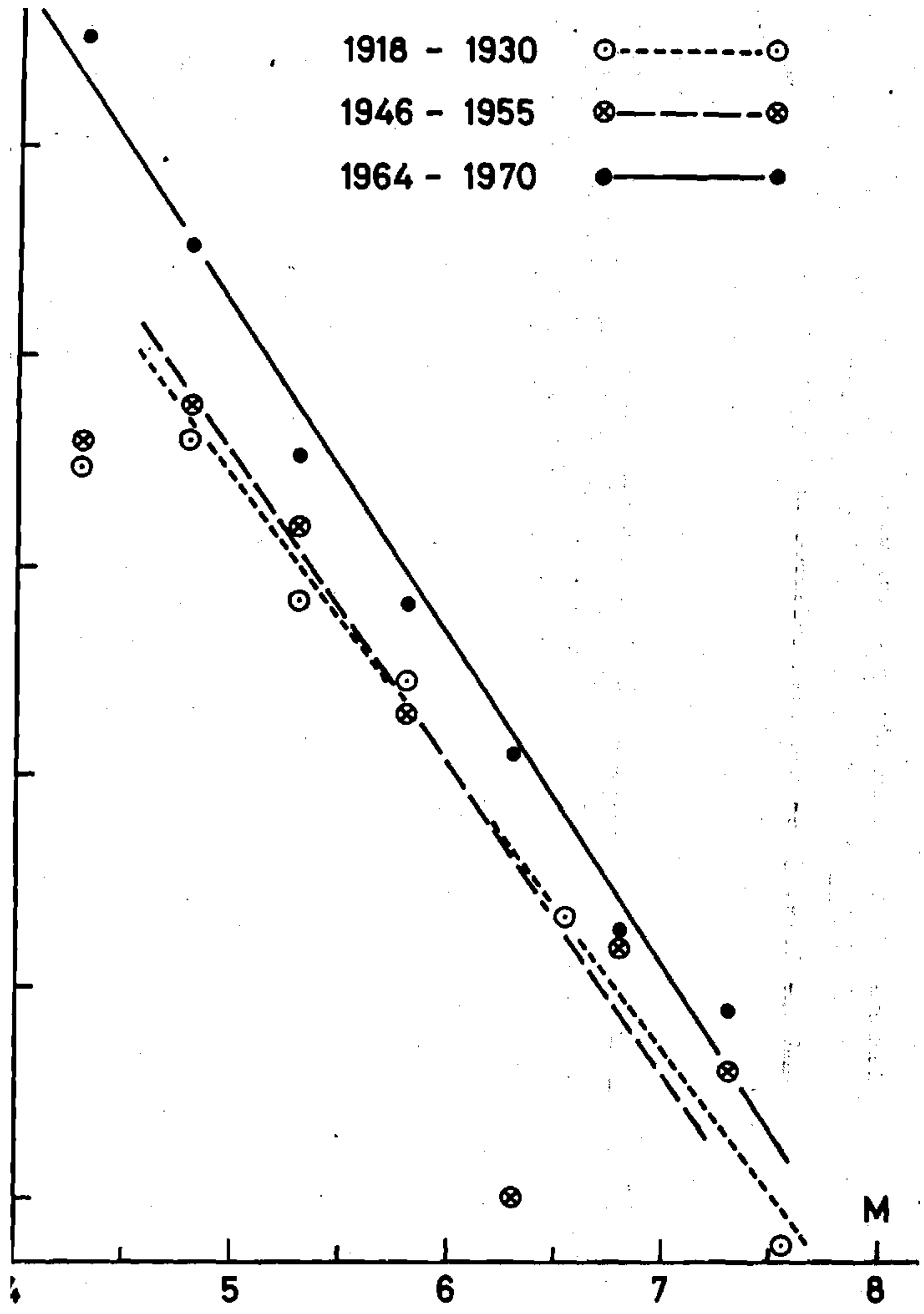

Fig. 1. Relations between number of earthquakes N and magnitude M for different intervals of time. N refers to half-unitintervals of M and has been reduced to an interval of 10 years.

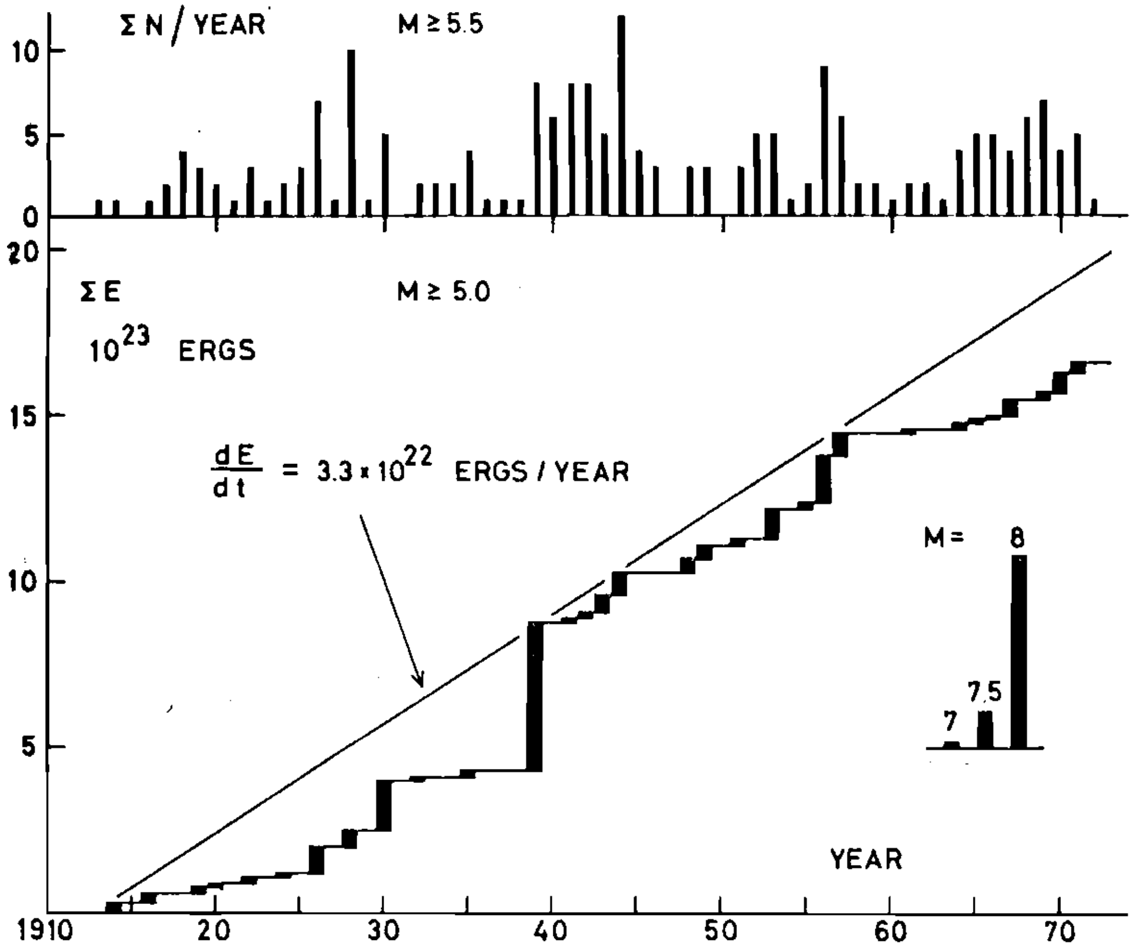

Fig. 2. Secular elastic wave energy accumulation and release in the investigated area, the latter plotted as annual energy sums for all earthquakes with M ≥ 5.0.
The upper plot gives the annual numbers of all earthquakes with M ≥ 5.5 within our area.
The years 1971-1973 have been added from Uppsala monthly bulletins.

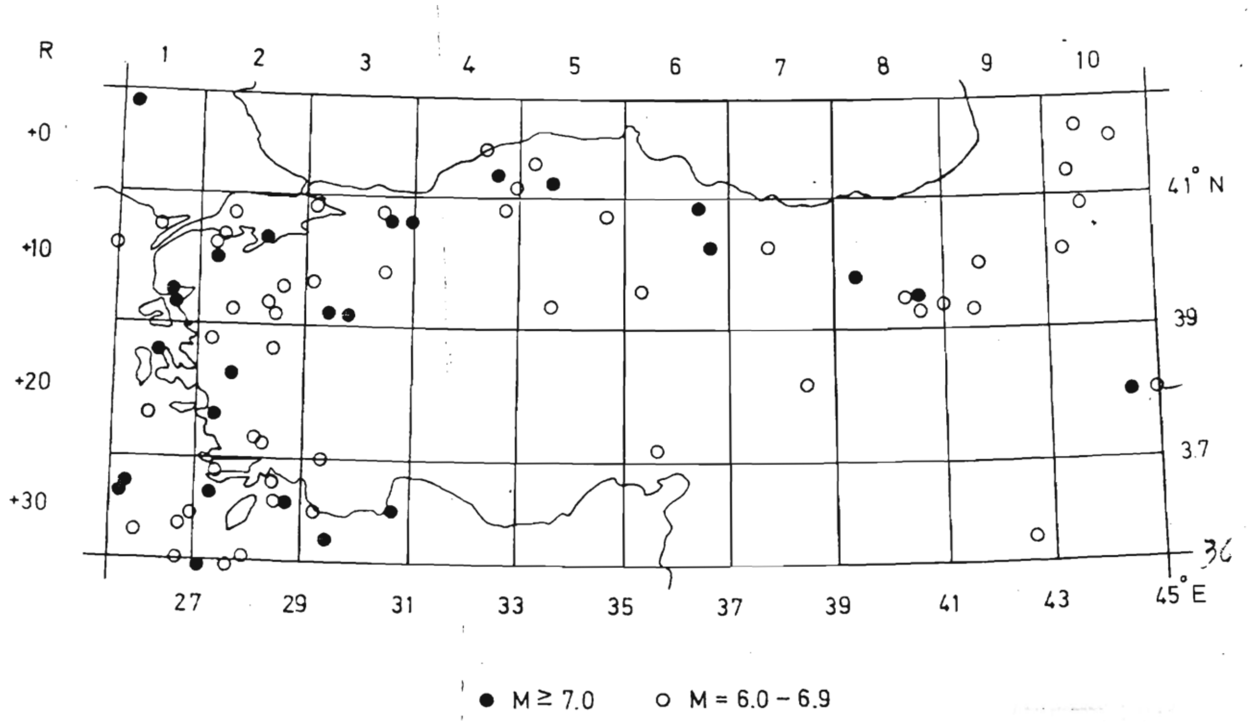

Fig. 3. Map of the area investigated, showing the epicenters of the largest earthquakes and the division of the area into regions R.

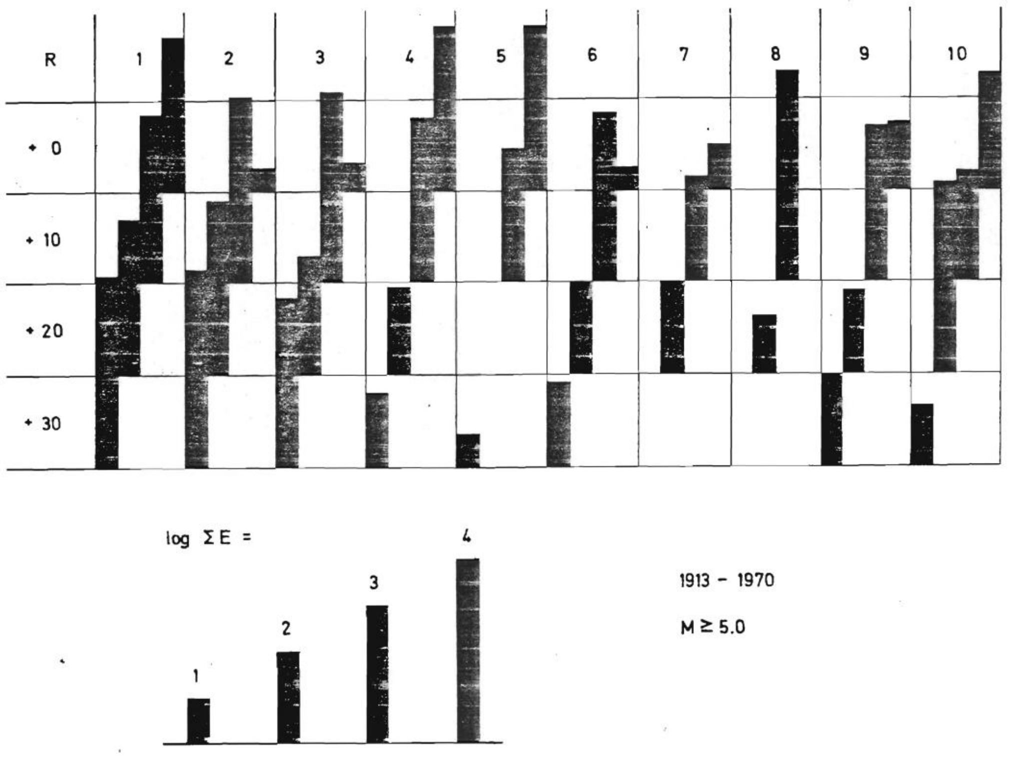

Fig. 4. Logarithmic energy sums per region for all earthquakes with M ≥ 5.0 for the whole interval 1913-1970. The unit for E is here chosen as 10^{19} ergs.

EXPLANATION OF CATALOGUE

Reference Numbers are assigned only to earthquakes with M ≥ 5.0, altogether numbering 450, for further use in the Epicenter and Magnitude Index at the end.

For the interval 1913-1963, results with standard deviations have been calculated by the present authors. The focal depth error is estimated to be ± 5 km for h ≤ 80 km and ± 10 km for h > 80 km. In case a focal depth could not be determined, depth values for other near-by events have been adopted, and such depth values are given with an asterisk (*). The data source is ISS, unless otherwise indicated.

For the interval 1964-1970, results (except M) are collected from ISC Regional Catalogues. Recomputations are also due to ISC, unless otherwise indicated. In calculations by ISC, standard deviations are generally given not only for origin time and coordinates but also for focal depth.

Throughout the whole interval 1913-1970, earthquakes not permitting computer recalculation have also been included, with appropriate references. The accuracy is in such cases generally not known, but according to some duplicate determinations found in the literature, errors may sometimes reach quite considerable amounts.

The magnitude M is the surface-wave magnitude throughout the whole catalogue. Its standard deviation may in general be estimated as around ±0.3 units, but it may be larger in individual cases, especially for smaller events. All magnitudes have been determined by us or derived from other given magnitudes by means of our conversion formulas, whence information on data source and number of observations does not apply to the magnitudes.

Internationally adopted abbreviations are used for stations and organizations.

EPICENTER AND MAGNITUDE INDEX

The index is arranged according to regions (R) as shown in Fig. 3, and is restricted to earthquakes with M ≥ 5.0. The reference is given here by four-digit numbers, the first two referring to the year, the last two to the reference numbers used in the main catalogue. For example, 1903 refers to the year 1919, reference number 3; 5712 refers to the year 1957, reference number 12, and so on. There are no events with M ≥ 5.0 within the regions 8, 25, 37 and 38.

Epicenter and magnitude index

Region	Area	M ≥ 7.0	M = 6.0 - 6,9	M = 5.5 - 5.9	M = 5.0 - 5.4
1	41-42.5 N 25.5-27 E	2805		2806, 2807, 2809, 2810, 2811	2808, 5314
2	41-42.5 N 27-29 E				2304
3	41-42.5 N 29-31 E				5713
4	41-42.5 N 31-33 E	4404	6809		4406
5	41-42.5 N 33-35 E	4309	4503, 5317	1903, 4415, 4501	2303, 3604, 3605, 4210, 4601, 5103, 6616
6	41-42.5 N 35-37 E				5405
7	41-42.5 N 37-39 E				6304
9	41-42.5 N 41-43 E				2402, 5701, 5702, 5703, 5904
10	41-42.5 N 43-45 E		1302, 2501, 4003	5912	2610, 2613, 4004, 5807, 6110, 6701
11	39-41 N 25.5-27 E	1907, 4416	1701, 6504	1702, 4418, 5501, 5601, 5802, 6802	1703, 2302, 3102, 4417, 5106, 5202, 5619, 6109, 6302, 6804
12	39-41 N 27-29 E	5303, 6410	3501, 3503, 4202, 4206. 4208. 6904, 6906	3502, 3901, 4207, 5104, 5204. 5304, 5313, 5315 6613, 6902, 6909, 7012	2401, 2803, 4203, 4205, 4301, 5003, 5305, 5308, 5309, 5402, 5406, 5906, 6409, 6905, 6912.
13	39-41 N 29-31 E	3907, 6704, 7002	2812, 4304, 5602, 6306	2612, 3904, 3906, 4809, 5714, 5715, 6707, 7010, 7011	2801, 3902, 3903, 3905, 4303, 4305, 4901, 5203, 5603, 5712, 5716, 5720, 6105, 6705, 7003, 7004, 7005, 7006, 7007, 7008, 7009, 7015
14	39-41 N 31-33 E	5711	5102	4407	1902, 4401, 4405, 4703, 4903
15	39-41 N 33-35 E		3801, 4211	1806, 2815, 4209	1904, 2814, 3802, 3803, 4419, 5718
16	39-41 N 35-37 E	1601, 4212	4005	2301, 4002, 4102	1401, 1807
17	39-41 N 37-39 E		2901	3910, 3911, 6001	2902, 7013
18	39-41 N 39-41 E	3909, 4907	6611, 6612, 6706	3009, 3908, 4110, 6505	3002, 3507, 4908, 4909, 5706, 5717, 5801, 6810
19	39-41 N 41-43 E		2404, 6607	4604, 5201, 6601	2405, 2406, 2502, 2503, 5306, 5907, 5909, 6608, 6702, 6911
20	39-41 N 43-45 E		2611, 3505	2104, 4108, 6805	3506, 6204
21	37-39 N 25.5-27 E	4905	4107	4911, 6908	1901, 2804, 4906, 5301, 5310, 5311, 5312, 5910

Epicenter and magnitude index (cont.)

Region	Area	M ≥ 7.0	M = 6.0 - 6,9	M = 5.5 - 5.9	M = 5.0 - 5.4
22	37-39 N 27-29 E	2802, 5002	4103, 4112, 4409, 6907	1808, 2004, 2601, 2602, 2813, 3702, 4101, 4104, 5404, 6501	2003, 2005, 2102, 2509, 2606, 4105, 4106, 4109, 4201, 4806, 5403, 5503, 6108, 6604, 6605
23	37-39 N 29-31 E		2603	1801, 2407, 2508, 3303, 4410, 6301, 6401, 6503	1804, 2510, 2701, 3603, 6602, 6606, 6615, 6708
24	37-39 N 31-33 E			3008, 4602	1802, 2001, 2103, 3101, 3402, 4605
26	37-39 N 35-37 E		4502	5207	6107
27	37-39 N 37-39 E		6403		4902, 5001, 5307, 6402, 6811
28	37-39 N 39-41 E				1501, 3001, 5002
29	37-39 N 41-43 E			3404	1301, 4111, 6603, 6609, 6610, 6614, 6807
30	37-39 N 43-45 E	3004	3005	3003, 3401, 4008, 4504	3006, 3007, 4701, 5205, 6808, 7001
31	35.5-37 N 25.5-27 E	5604, 5605	1805, 4204, 5612, 6202	2002, 3203, 4001, 4413, 4603, 5208, 5209, 5609, 5610, 5613, 5615, 6101, 6203, 6709, 6801, 6816	2609, 3302, 3403, 3504, 4414, 5302, 5606, 5607, 5608, 5611, 5614, 5616, 5617, 5618, 5705, 5806, 5809, 5905, 6404, 6411
32	35.5-37 N 27-29 E	2608, 4801, 5708	2201, 2202, 3301, 5707, 6106	1906, 2203, 3204, 4306, 4308, 4403, 4408, 4412, 4807, 5710, 5805, 5902, 6406, 6506, 6806	1803, 1905, 2101, 2204, 3201, 3202, 4302, 4402, 4802, 4803, 4804, 4805, 4808, 4904, 5004, 5206, 5318, 5401, 5407, 5704, 5709, 5719, 5803, 5808, 5903, 6003, 6102, 6103, 6104, 6201, 6305, 6405, 6407, 6803, 6812, 6813, 6814, 6815, 6817, 6910, 7014
33	35.5-37 N 29-31 E	1402, 2604	6901	2504, 4307	2505, 2506, 2507, 2605, 2607, 3701, 4007, 5105, 5316, 5901, 5908, 5911, 6002, 6408, 6502
34	35.5-37 N 31-33 E			2702, 4006	2403, 3601, 3703, 6903
35	35.5-37 N 33-35 E				4702
36	35.5-37 N 35-37 E			3602, 5101	1502
39	35.5-37 N 41-43 E		4411		
40	35.5-37 N 43-45 E				4910, 5804, 6303, 6703